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POTENTIAL TRANSPORT OF SPRAY MATERIALS BY SLOPE WINDS: AN INTERPRETIVE LITERATURE SURVEY

PROGRAM WIND

COOPERATIVE ATMOSPHERIC RESEARCH

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POTENTIAL TRANSPORT OF SPRAY MATERIALS BY SLOPE WINDS: AN INTERPRETIVE LITERATURE STUDY

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A number of complications and exceptions to this flow scenario are discussed. Scaling arguments are developed to estimate the plausibility of penetration of downslope flow to the valley floor. Transport by early morning upslope flows is also discussed although upslope flow has been studied much less than downslope cold air drainage.

Dispersion of transport of spray materials by turbulent motions is reviewed. A number of different turbulent regimes may occur; transport by intermittent turbulence occurring with very strong stability is least understood. Flow immediately above the cold air drainage may also lead to significant horizontal dispersion of spray materials.

A relatively simple operational technique is proposed for assessing the probability of transport of suspended spray material to the valley floor. This technique requires experimental calibration.

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Foreword

Program WIND is a cooperative applied research program between the USDA Forest Service and the U.S. Army Atmospheric Sciences Laboratory, White Sands Missile Range, New Mexico. The object of Program WIND is to evaluate meteorological and dispersion models.

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Preface

This interpretive study attempts to identify the most important features of cold air drainage which impact on atmospheric transport of particulates such as inadvertently suspended spray droplets. Certain classes of cold air drainage are expected to transport suspended droplets to lower elevations with relatively small dilution and thus constitute the potentially most serious situation.

Cold air drainage generally dominates transport during the night and in the early morning hours if ambient winds are weak and skies are clear. Aerial spray applications are usually conducted in early morning when cold air drainage is still maintained on many days.

Even cold air drainage circulations are much more complicated than most would expect. Several recent field programs have shown that existing theories of cold air drainage cannot describe most drainage flows over complex terrain such as typically occur in western forests. The details of such drainage flows and interaction between drainage flows from different slopes and pre-existing air in valleys are not readily modelled. However, there is hope that certain basic features of such flows can be used to predict the likelihood of certain patterns which affect spray transport. The same hope applies to transport by upslope currents, although less is known about such flows.

<u>This study does not attempt to mention all of the studies on cold air drainage or even a significant fraction of them but rather sort out those which are most relevant to realistic transport problems</u>. Indeed most theoretical studies provide only limited information on the drainage flows in the complex terrain of western forests. Many of the previous observational studies are specific to the unique terrain signature of the research site and

do not include sufficient observational information to allow generalization to other situations. Studies which were directly consulted for the present work are listed in the references at the end of the report. The text itself is interrupted with citations only when such references have contributed unique and significant findings. The remaining discussion in the text represents a synopsis of many studies in the literature. In general, the large number of references in German are not cited. However, considerable use has been made of the survey of German literature by Schnelle.

Perhaps the most important and most tentative part of this report is the sections on proposed operational techniques for spraying decisions (Section 8), and the brief section on recommended field work (Section 9).

Larry Mahrt

Corvallis

22 August 1985

1. Introduction

Spraying applications are normally carried out during weak wind situations to avoid extensive drift and other technical difficulties. Such weak wind conditions occur most dependably in the morning hours with minimal synoptic pressure gradient and clear skies. Under such conditions the transport of suspended spray materials is usually controlled by local circulations including slope circulations. Such circulations occur over even weak slopes. Since the turbulent activity in such flows is usually weak, such currents may transport suspended particles with small dilution.

An enormous number of observational and analytical studies have been devoted to downslope drainage of cold air, many of which are summarized in the reference books of Geiger (1975), Yoshino (1975), Schnelle (1963a,b), while some special aspects are summarized in Atkinson (1981) and Barry (1981). However, some of the most important advances in the study of such flows have been reported recently following several major field programs in the United States, Greenland, Denmark, Italy and West Germany. These field programs employed instrumentation systems which are considerably more advanced than those used in field studies just a few years before. Such new instrumentation included improved sampling of tracers and use of low-flying aircraft with fast-response instrumentation. Some of these results have just been reported in the published literature and contract reports. In spite of these advances, many features of downslope flows remain unexplained.

Recent field programs and laboratory studies have also shed new information on the behavior of upslope flows associated with surface heating. This subject has received much less attention than the study of downslope flows and even the most basic features of upslope flows cannot be reported without some speculation.

An important first step is to establish some perspective on what aspects of transport by slope flows can be explained and what is beyond our ability to describe. Downslope drainage flows are difficult to explain or predict because of several complications:

1. Each downslope flow is unique to the specific terrain situation. The flow closest to the ground responds to the slope in its immediate vicinity while the flow a little higher above the ground responds to the slope on somewhat larger horizontal scales. Drainage flows down different slopes may merge and mix or the colder of the two may undermine the warmer flow. The patterns of cold air drainage and heated upslope flows over complex terrain typical of western national forests appear more as a form of quasi-two-dimensional turbulence on the scale of the terrain irregularities ("drainage turbulence") rather than a deterministic phenomena. Even when the slope flow over a given local slope behaves in a regular fashion, the interaction of slope flows at the interface between two slopes cannot be predicted. Many such encounters may occur as a reference parcel descends to lower and lower slopes.
2. Turbulent mixing within drainage flows over complicated terrain often violates existing theoretical or empirical laws. The turbulence is often intermittent and not in equilibrium with local surface conditions. Much of the turbulence may be generated by shear at the top of the drainage flow and not participate in direct communication with the surface as assummed in most models.
3. The interplay between subcanopy flow and flow immediately above the canopy is not well understood. In some cases the drainage flow may actually find channels of open areas in the canopy as included in the model of Bergen (1969).

4. The interaction between slope flows and meso and synoptic scale flows is poorly understood in spite of some useful studies of such interactions. The formulation of general principles for such interactions is essentially not available.

Because of these complications, theoretical models, alone, are inadequate tools for operational assessment of spray transport. Empirical guidelines, even if limited, must be formulated. In the following interpretive survey of the literature, results of key studies will be discussed which allow limited empirical formulation of transport of suspended spray materials by slope circulations. Recommendations for future field work or analysis of existing data will then be suggested.

Much of the interpretive analysis will be framed in terms of specific questions. For example, will suspended spray particles be transported by downslope flows to valley floors which often contain inhabitants and occasionally sensitive agricultural products? Does significant amounts of suspended material reach the valley floor indirectly through mixing? We begin in Section 2 with a survey of classical concepts and some recent modifications of such concepts.

Before proceeding with this discussion, we will agree not to unravel the theoretical distinction between drainage gravity and katabatic flows. Sometimes drainage flows are defined to include only flow of cold air down an adjacent slope whereas katabatic flow is defined to be the flow of cold air down the slope on which it was generated (Fitzjarrald, 1984). Several other definitions of katabatic flow have been used in the literature. With complex terrain such distinctions are often not possible and will not be used here.

The usual distinction between valley and slope winds is also ambiguous in complex terrain. In this report the term valley or "main valley" will be

reserved for valleys with a broad relatively level floor. Side valleys with little floor will be considered as irregularities of the slope or side valleys. Terminology used in the literature is usually defined only in terms of relatively simple terrain geometry which does not readily apply to many practical situations.

2. Basic concepts

Analytical treatments (see Mahrt 1983 for a partial survey) are not applicable to much of the complex terrain of western national forests partly because they assume constant slope and equilibrium turbulence and necessarily neglect other important complications noted in the Introduction. Over quite simple slopes, such analytical considerations seem to describe some features of the flow. As one example, Bergen (1969) found that drainage flows down a relatively simple, partially forested, slope in Colorado were well described by similarity theory. Horst and Doran (1985) found that relationships from Ellison and Turner (1959) and Manins and Sawford (1979a) successfully described drainage flow down a relatively simple slope in Central Washington. However, important elements of slope flows of more complicated terrain are not included in existing theories. Some features of slope flows over complex terrain can be approximated in numerical models with considerable effort and cost. Such efforts are of scientific interest but probably too expensive and uncertain, and require too much input data for operational use.

Literally hundreds of observational studies of downslope gravity flows have been completed. Most of these studies have been implemented over simple terrain for obvious scientific reasons. Those observational studies over complex terrain have not led to general principles which allow reliable prediction of flow behavior at an unstudied site. However, such observations

along with some basic physical considerations do allow formulation of a few useful concepts which we now summarize.

a) Fundamental concepts

The first essential concept is trapping of cold air in low-lying areas sometimes referred to as cold air lakes. Small scale preferred locations for trapped cold air are often referred to as "frost pockets". When weak or non-existent shear cannot maintain even weak turbulence, downward mixing or warmer air is minimal leading to especially cold temperatures at the surface.

The surface air at elevations somewhat higher than the trapped cold air (Fig. 1) is not as cold in spite of experiencing significant nocturnal cooling. This region on the slope above the cold air lake is sometimes referred to as the thermal belt (Geiger, 1975; Schnelle, 1963b). Surface air in this region is often participating in downslope drainage of cold air since the air is relatively cooler than the free air at the same elevation. However, turbulent mixing within this drainage flow acts to moderate the total cooling (e.g., Manins and Sawford, 1979b) so that it is warmer than surface air at the bottom of the slope. In this situation, the downslope drainage will flow over the top of the cold air trapped at lower elevations. When the trapped cold air maintains little turbulence, particles in the "cold" air drainage will be transported over the top of the even colder trapped air with little downward mixing into the interior of the trapped cold air. This overriding is the topic of Chapter 3.

Often drainage circulations penetrate directly to the floor of the valley, especially early in the evening before development of a cold air lake. With significant slope of the valley floor, surface flow may descend down the valley sometimes reaching speeds in excess of 5 ms^{-1} (Whiteman and Barr, 1984), possibly leading to transport to more populated areas. With a

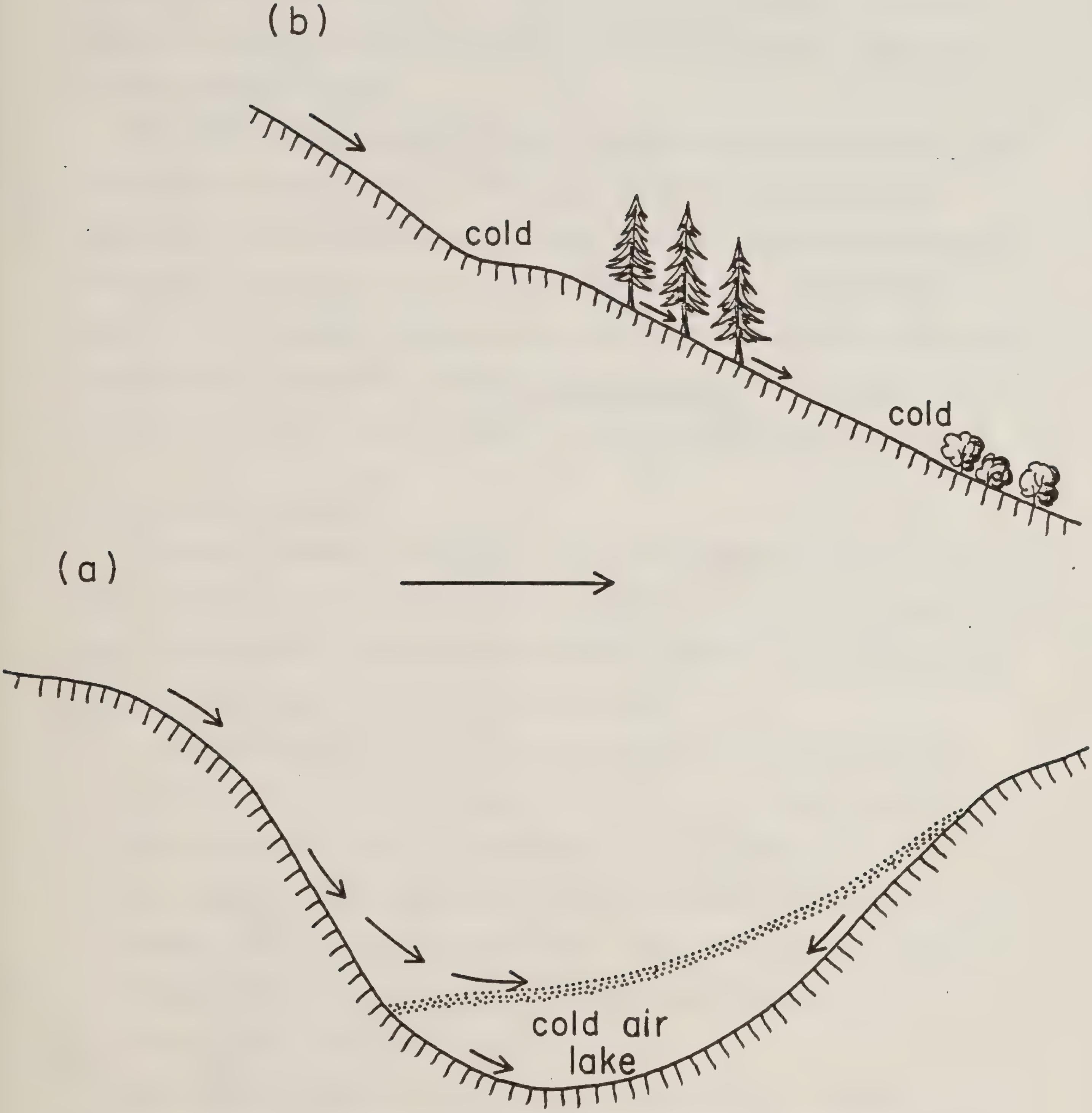

Fig. 1. (a) Idealized sketch of a simple drainage flow which overrides colder air located at the valley bottom. (b) Location of cold trapped air due to local concave terrain curvature or thick canopy (see discussion on p. 9).

mountain-plain configuration, the downslope drainage of cold air generally spreads over the plain displacing pre-existing air as recently studied by Blumen and Hootman (1983).

To assess the possibility of direct transport to the valley floor versus overriding pre-existing air at the valley floor, we must consider the properties of the drainage source regions and certain dynamical considerations which will be outlined below. In some cases the downslope drainage may pulsate in both strength and temperature and may periodically reach the valley floor directly or indirectly through episodic mixing (Gryning et al., 1985). In addition, cold air may be trapped at various locations along the slope.

b) More complex terrain

In western forests, the terrain is considerably more complicated than those simple valley-slope configurations described by the above concepts. In more complex terrain, suspended spray materials may participate in a variety of possibilities some of which are now summarized:

1. In the simplest case (Fig. 2a), droplets may still be transported directly down the various slopes to the floor of the main valley and then down the valley toward the valley mouth as discussed above.
2. The droplets may be transported by drainage flows which continually merge and mix with drainage flows from other upland side valleys so that the suspended material is substantially diluted before reaching the floor of the main valley (Fig. 2c).
3. The drainage circulation may override a second drainage current (Fig. 2d) which is considerably colder or may override colder preexisting air at the floor of the valley as discussed above (Fig. 2b-c). The cold air lake may not have a definite top but rather a relatively thick transition layer possibly consisting of several sublayers associated with previous

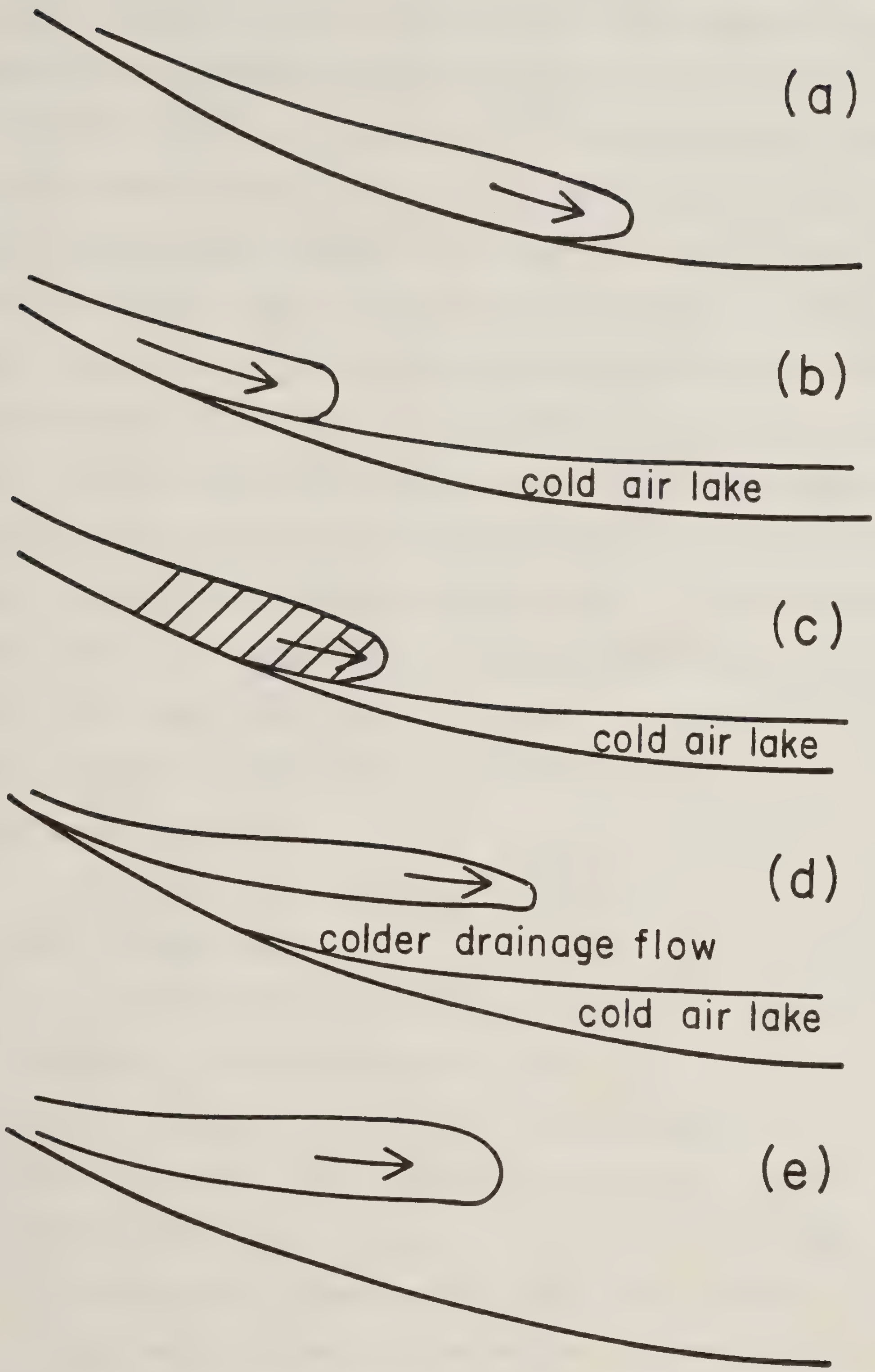

Fig. 2. Idealized sketch of several classes of transport of plumes of suspended material released near the surface.

overriding. In these various cases the spray material reaches the valley floor only indirectly through diffusion and is not expected to be observed with any significant concentration at the valley floor.

4. The suspended materials may fall into, or flow into, trapped cold air pools well above the valley floor and thus never reach the valley floor. Microclimatic locations favorable for trapped cold air are often identified by changes of vegetation associated with adaption to the "frost pocket" microclimate. The connection is as follows. Cold air drainage and associated shear leads to generation of turbulence even if weak. This turbulence leads to downward mixing of warmer air and thus reduces the total cooling at the surface. Where drainage flow is impeded such downward mixing does not develop leading to especially cold temperatures. Droplets suspended into such trapped cold air are likely to remain there because the airflow is virtually nonexistent and turbulent mixing is minimal. Trapped cold air is often associated with one of the following circumstances:

   a) flat plateau regions or bench-like terrain;

   b) shallow depressions;

   c) partial blockage of drainage flow due to terrain constrictions and sharp bends in narrow side valleys; and

   d) blockage of drainage flow by brush and dense vegetation. Here the textbook analogy of cold air drainage with drainage of water breaks down. Air is much more viscous. In brush, a micro-boundary layer develops around and downstream from each little twig and leaf. If the micro-boundary layer wakes merge, the drainage flow is seriously retarded. In more mature canopies, the wakes behind each tree trunk

do not usually merge and some subcanopy drainage is permitted as sketched in Fig. 1.

5. The spray materials may be suspended into the ambient flow and transported away from the spray region before reaching near-surface air or the local surface air may be sufficiently warm compared to the air at lower elevations that local transport is primarily horizontal away from the slope (Fig. 2e). In such cases the number of transport possibilities are large. However, direct transport to the valley floor would be less likely (but not necessarily improbable) under conditions of clear skies and relatively weak ambient flow since the ambient flow would be warmer and more buoyant compared to the cold air at the valley floor.

c) Ambient flow

We now discuss the influence of ambient flow on the cold air drainage itself. Even relatively weak ambient flow will influence most downslope drainage flows. With strong ambient flow, the drainage current will be eliminated entirely. Weaker ambient flow can significantly modify the slope flow directly through downward mixing of momentum from the ambient flow. Enhanced shear between the ambient and downslope flows increases the probability of significant mixing (Horst and Doran, 1985; Mahrt, 1985). The corresponding downward mixing of warmer air also reduces the buoyancy deficit of the drainage flow which in turn weakens the generation of such flow.

The prediction of transport of suspended spray materials requires as a minimum the prediction of the existence of drainage flows in situations with significant ambient flow. Slope-valley winds are often seriously disrupted by ambient winds greater than 5 ms^{-1} (Horst and Duran, 1985) although in deep valleys they may survive ambient flow greater than 10 ms^{-1} (Davidson and Rao, 1958, 1963). In the tracer study of Gryning and Lyck (1983), the obvious

influence of the direction of the ambient flow with respect to the release point and sample stations become evident. Drainage flows closer to the ridgetop are more easily eliminated or strongly modified by overlying flows (Gudiksen et al., 1984). Horst and Doran (1985) found that, at least for one site, the existence of drainage flow was related to the strength of the integrated buoyancy deficit relative to the strength of the ambient flow.

Even when drainage flows are not eliminated, they may be substantially delayed by opposing ambient flow (Fitzjarrald, 1984). In the case study of Mahrt and Larsen (1982), drainage flow was prevented by the ambient flow of opposite direction until the slope Richardson number decreased below a critical value which seemed to be consistent with earlier laboratory studies. Bowen et al. (1981) also noted that drainage flows arrive as a surge when they are first retained by opposing ambient flow. Other studies of this surge include Blumen (1984) and Hootman and Blumen (1983).

The ambient flow is often quite complex since it can be driven by synoptic scale pressure gradients, the usual abundant free oscillations as well as systematic variations associated with larger scale terrain features. In the study of cold air drainage studied by Hahn (1981), overlying air was thought to participate in a nocturnal inertial oscillation as well as respond to thermally-induced pressure gradients on a larger scale. Several specific contributions to the wind above drainage flows in the Geysers Geothermal Resource Area are noted in Orgill and Shreck (1985). With weak wind conditions, the ambient flow direction is usually quite variable and can transport spray materials in an unpredictable fashion. Since spray materials in the ambient flow can be mixed downward to the surface at a later time, the influence of spray transport by the ambient flow is a formidable prediction

problem. The influence of the ambient flow on spray transport is briefly reconsidered in Section 8.

3. Overriding

The possibility of one cold air drainage current overriding another colder current or overriding trapped cold air is of obvious importance to the problem of predicting spray transport. I expect this possibility to be common in western forests. Although such overriding is not considered in the majority of studies of cold air drainage, it has been long recognized as a typical feature of nocturnal conditions. For example, in the early study of Heywood (1933), the cold air drainage was found to descend to the valley floor only in the early part of the evening. As the evening proceeded, the valley bottom filled with cold air and subsequent drainage flow no longer reached the valley floor. It was surmised that the drainage flow spread over the top of the trapped cold air.

Such overriding has been noted from time to time in subsequent studies. However, a number of studies completed in the past five years indicate that such overriding might be common (e.g., Lenschow _et al._, 1979; Barr, 1983). Overriding is most dramatically illustrated in the tracer plume observations of Lange (1981). In the study of Gryning _et al._ (1985), drainage flows were found to systematically override colder preexisting air at the valley floor although periodic mixing appeared to take place at the interface between the two. The edge or minifront where the drainage flow overrode the valley air was found to periodically oscillate apparently due to low-frequency internal gravity waves trapped by larger-scale terrain features.

While overriding of one nocturnal current over a colder one has been documented in a number of studies, the dynamics of such overriding has not

been detailed. In the recent study of Lenschow _et al_. (1979), flow apparently responding to the slope on a larger scale overrode colder shallow motions which drained down small valleys perpendicular to the larger scale flow. This regime survived for an hour or more after sunrise at some locations. The nocturnal multi-layer flow structure observed by Barr and Clements (1981) was also attributed to forcing on different scales.

In these studies, the coldest flow adjacent to the ground appeared to be driven by the local slope. In the study of Hasenjäger (1980), the downslope flow of cold air associated with larger scale features of the terrain arrived at later times leading to a buildup of several different layers whose origin could not be unambiguously determined. The author surmised that mixing within each layer was minimal but that some shear driven turbulence developed at the interface between layers. Even when the drainage current from the side valleys form a confluence rather than obvious overriding, the mixing between the two currents appear to be incomplete (Schmel, 1981).

The thermodynamics of each current must be considered before attempting to predict overriding. Drainage currents directed down the slopes are expected to be sometimes warmer than air at the valley floor because the shear corresponding to the gravity current generates turbulence and downward mixing of warmer air as discussed in Section 2. In contrast, the trapped or slow moving air at the valley floor will not benefit from warming due to mixing. As a result the valley air continues to cool due to contact with the radiatively cooling surface and also due to clear air radiative cooling. The latter process is often neglected but has been found to be important in several recent studies including Garrett and Brost (1981) and André and Mahrt (1982). The gravity flow on the slope also cools by radiative processes, but this cooling is partially compensated by the warming due to turbulent mixing.

This warming process has been recognized in a large number of studies over the past fifty years and is credited with the formation of the thermal belt along the slope. This mixing process appears to have been first formulated in a geophysical model by Manins and Sawford (1979a) by means of an entrainment parameterization. Such a formulation was motivated by the earlier laboratory experiments of Ellison and Turner (1959). With entrainment, the gravity current is envisioned as thickening (less any divergence effects) through engulfing warm air from above. In other terms, turbulent eddies scoop in blobs of warm air from the overlying warmer air and thus increase both the mass and the temperature of the drainage flow. This entrainment would not only dilute the concentration of suspended material in the drainage current but would also increase the buoyancy of the drainage current thus increasing the probability of overriding at the bottom of the slope.

The process of entrainment is probably most relevant in fully turbulent drainage flow with significant speed as would occur over relatively steep slopes. An entrainment relationship seems to work well in the recent observational study of Horst and Doran (1985). In slower moving cold air drainage, the turbulence may be only intermittent. In this case, turbulence often periodically decays which effectively corresponds to conversion of turbulent fluid back to non-turbulent fluid. While this type of activity could be included in the process known as "detrainment", a way of formulating such a process does not exist, at least in a form which would be applicable to the spray transport problem. In any event the concept of detrainment also allows for the possibility of air in the drainage current to be ejected into the overlying fluid by turbulent elements. Such a possibility is consistent with a number of recent tracer experiments. Such ejected air would then be transported by the ambient wind.

Of most importance here is that turbulent mixing leads to a reduced cooling rate or even net warming of the cold air drainage. Since this mixing is thought to be strongest over steep slopes (other factors constant), we might expect the drainage flow over the steeper of two merging slopes to be warmer and thus override a merging drainage current from a less-steep slope.

The buoyancy of a given gravity flow also depends on adiabatic warming as it descends the slope and depends on the temperature of the source region. The temperature of the air in the upstream or source region depends on a number of factors which we now summarize.

1) The air in the source region will be cold if it is slowly moving and thus characterized by little mixing.
2) Stronger radiative cooling will result if the overlying air in the source region is particularly clear and free of clouds, fog and particulates.
3) Stronger cooling results with minimal heat flux from the ground. Heat flux from the soil is least when the soil is light (more sand than clay) and when the soil is dry. The moisture content of the soil is of particular importance since the thermoconductivity of the soil may vary by orders of magnitude with changes of soil water content. Thus, colder air is likely to form over regions with dry light soils.
4) If the ground is covered with dry organic debris (needles, leaves, dead grass, etc.), then the heat flux from the soil will be very small. The thermoconductivity of the dry organic debris is so small that it may act as a thermal insulator and therefore leads to greater surface cooling at night.
5) Subcanopy drainage flows are usually not as cold as drainage flows originating over open ground. Downward radiation emitted by the canopy greatly reduces the cooling at the underlying surface.

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6) Bodies of water, due to their high heat capacity, cool slowly at night and in most cases would significantly warm any drainage currents flowing over such water. This excludes deeper bodies of water in spring when the water temperature may be colder than even the minimum air temperature.

Using the above principles, it is possible to estimate (with some error) which regions are likely to lead to the coldest air. Then, examination of the terrain would allow estimation of the probability of a given drainage flow reaching the valley floor. Such assessments would be most useful if the terrain and character of the surface was relatively well-known but suitable atmospheric observations were not available. Such an assessment would necessarily be subjective. Before attempting to suggest more objective approaches it will be necessary to examine the most basic dynamical features of drainage flows and overriding.

4. Scaling arguments

The problem of overriding has not been previously considered in terms of theoretical analysis. It is therefore of educational use to formulate simple scaling arguments. Such analysis will not be of operational use but will provide an order of magnitude evaluation of the plausibility of certain flow responses.

The simplest possible formulation can be constructed in terms of the downslope momentum equation for idealized, steady-state, drainage flow of constant potential temperature deviation from the ambient flow. Neglecting turbulent transport and pressure effects, we obtain a balance between advection of momentum and buoyancy

$$u\frac{\partial u}{\partial x} = g\frac{\theta}{\theta_0} S \qquad (1)$$

or

$$u = \left[\frac{g}{\theta_0}\,\theta S x\right]^{1/2}$$

where S is the ratio of terrain slope assumed to be constant and small, x is the downslope direction and u is the downslope speed, θ is the potential temperature deficit and θ_0 is the scale value of potential temperature. If the terrain slope is not small, then the dynamics is more complicated (Mahrt, 1982).

When the potential temperature deviation from the ambient flow is negative, downslope flow is generated by the buoyancy term. However, if the downslope flow attempts to penetrate into colder air, the potential temperature deviation becomes positive and the buoyancy attempts to decelerate the downslope gravity flow. The downslope flow will continue to penetrate until it has exhausted its inertia represented by the left-hand side of (1). In terms of energy arguments, the flow descends until its kinetic energy has been converted to potential energy.

To obtain the penetration distance into the colder air, we integrate (1) with respect to downslope distance and obtain

$$x_f - x_i = u_i^2/\left(g\frac{\theta}{\theta_0} S\right) \qquad (2)$$

where the subscript f indicates the location where the motion of the downslope flow is arrested and the subscript i denotes the initial velocity where the downslope flow enters the cold air lake. When the motion is arrested,

buoyancy effects will then accelerate air upward but perhaps not before some spray material has mixed into the trapped cold air at the valley floor. The important issue becomes whether the drainage flow penetrates a significant distance into the cold air lake compared to the total dimensions of the cold air lake.

As an example, consider an initial downslope speed of 1 ms^{-1} for the case where the cold air lake is 3 C colder than the drainage flow and the slope is 5%. Then (2) indicates that the drainage flow will continue about 300 m into the cold air lake before buoyancy forces have consumed the initial kinetic energy. This penetration has to be considered significant for many spray applications particularly if the width of the valley is not large compared to a few hundred meters.

Note that the 350 m penetration distance for this example corresponds to a vertical descent of 15 m. In other terms, if the depth of the cold air lake is not large compared to 15 m, then the penetration of the drainage flow can be considered as significant and one must allow for the possibility that significant spray material reaches the valley floor. However, this scaling computation is only a plausibility estimate. Eq. (2) could overestimate the penetration distance since it neglects turbulence effects and pressure gradients.

The order of magnitude of the downslope flow speed prior to encountering the cold air lake can be estimated by assuming a balance between buoyancy and the turbulent drag as in Prandtl (1942), Defant (1949), Ball (1956), Munro and Davies (1977), and Petkovsek and Hocevar (1971). Formulating the turbulent drag in terms of a drag coefficient, the momentum balance becomes

$$g\frac{\theta}{\theta_0}S = C_D u^2 \ .$$

The equilibrium solution is then

$$u = \left[g\frac{\theta}{\theta_0}\ S/C_D\right]^{1/2} \ . \qquad (3)$$

The surface drag coefficient, C_D, for stably stratified flows is typically 10^{-3}. In the case where turbulent mixing of momentum at the top of the drainage flow is important, then the drag coefficient should be augmented. If the ambient flow is not negligible, then the analysis becomes more complicated. For a typical buoyancy deficit of 3 C and again chosing a slope of 5%, the equilibrium flow is estimated to be a little more than 2 ms^{-1}.

Relationships (2) and (3) could be used in concert to obtain a rough estimate of possible penetration or overriding as the drainage flow encounters a cold air lake. Of course the developments leading to (2-3) have made many assumptions which are not met in actual drainage flows. In fact, the concept of a cold air lake with a sharp boundary is only a crutch for referring, in a simple way, to a more complex phenomena. Thus, the above analysis represents more of an initial stage of "homework" rather than a proven operational tool. In the following sections more specific, but still tentative, procedures will be suggested which will allow for the estimate of the likelihood of transport of spray materials to the valley floor.

5. Diffusion of spray materials

In the preceding section, we examined the bulk transport of the spray materials by the drainage flow. However, even if the drainage flow does not extend to the valley floor, some suspended materials may reach the valley floor indirectly through diffusion. For example, if spray materials are advected over the top of the cold air lake, either by overriding of drainage flow or by the ambient flow, then intermittent turbulence could mix some material downward to the valley floor although downward mixing of large concentrations would normally not be expected.

Interfacial shear at the top of the surface cold air could generate turbulence and enhance diffusion to the valley floor. At the same time, any directional shear is expected to indirectly lead to greater horizontal dispersion of suspended spray materials which can substantially reduce concentrations at any one given point (Kristensen et al., 1982). For example, suspended material released and transported in the drainage flow may diffuse upward across the interface and subsequently become advected by the overlying ambient flow. Such overlying flow is often quite variable in complex terrain leading to partial horizontal dispersion of spray material (e.g., Barr et al., 1983; Gudiksen et al., 1984; see also discussion in Chapter 2).

Before speculating further about diffusion of spray materials it is necessary to briefly summarize various turbulence regimes. This summary assumes special importance because the vast majority of models of drainage and contaminant dispersion are based on only the "classical" case while several of the other cases appear to be frequently important in nocturnal drainage situations.

In the classical case, substantial turbulence is generated by surface based shear associated with "relatively" strong flow. This turbulence extends

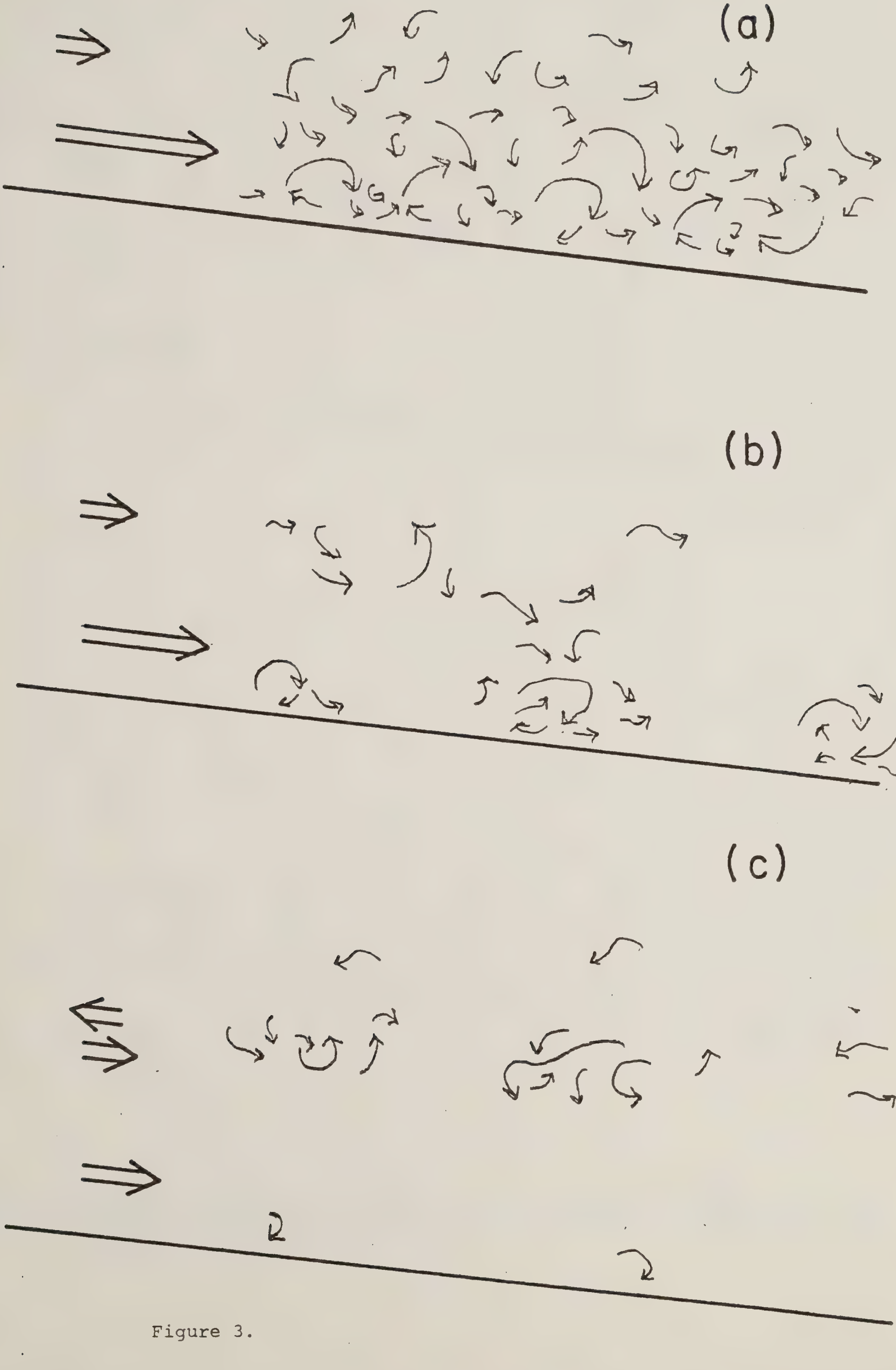

Figure 3.

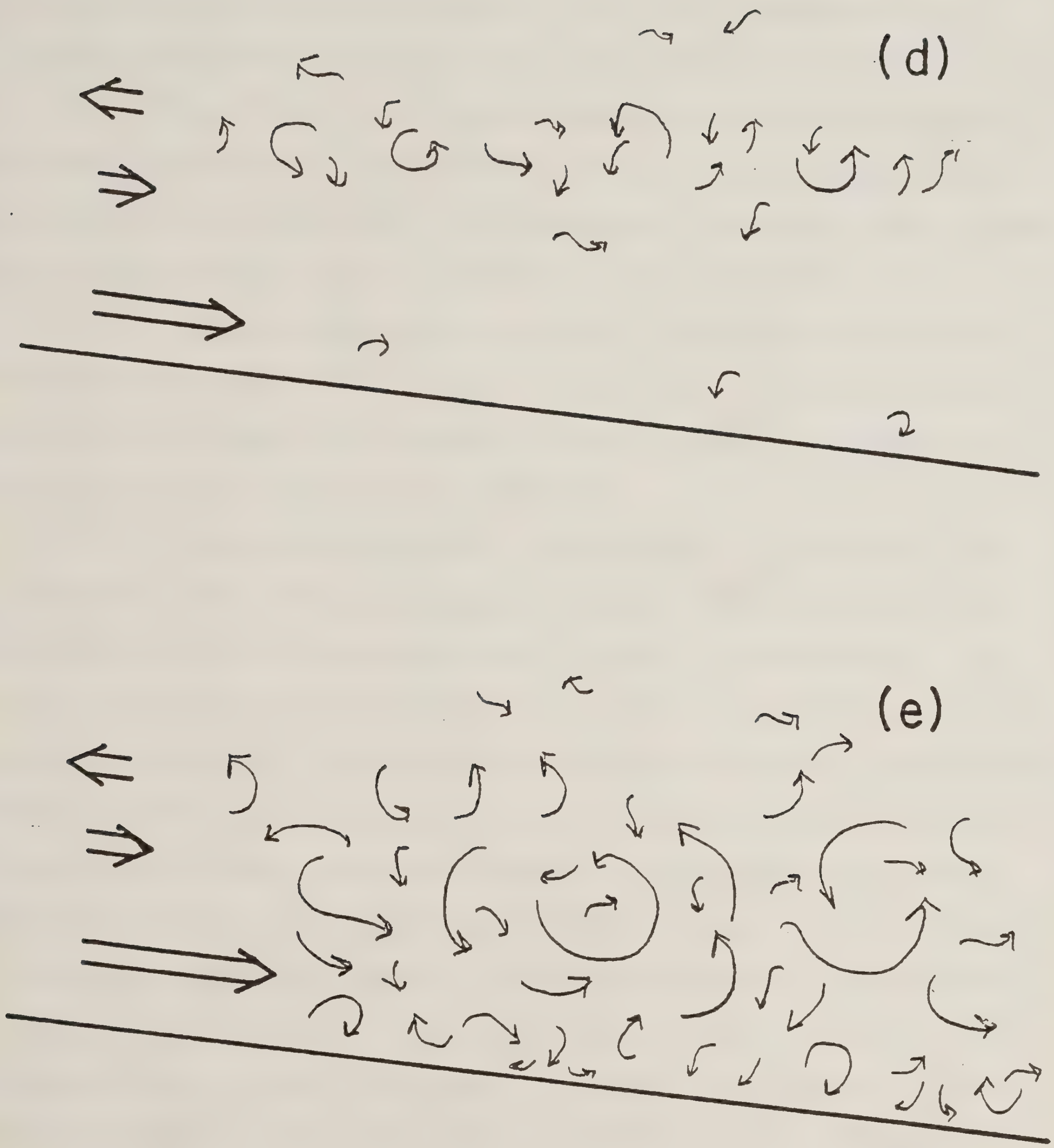

Fig. 3. Idealized sketches of several classes of turbulence regimes which are found in drainage flows.

throughout the drainage flow (Fig. 3a) although it decreases with height and vanishes at the top of the drainage flow. Materials released within the drainage flow are diffused across this flow but are primarily contained within it. Materials above the drainage layer in general do not mix into the drainage flow. One exception is that suspended material immediately above the drainage flow may be entrained into the drainage flow when this layer is deepening due to turbulent mixing. Several variations on the classical case have been observed where the depth of the turbulence, the depth of the cold air drainage and the depth of the surface inversion layer do not coincide. Such variations in drainage flows are not well understood and their inclusion is not of general use for the present discussion.

If the flow speed is only modest, the turbulence for the bulk of the drainage flow occurs only intermittently (Fig. 3b). This intermittency has been observed in many studies (see Blumen, 1984 for a recent example). As shear across the flow builds (and Richardson number decreases), the bulk shear leads to overturning. Ensuing turbulent mixing reduces the bulk shear and the turbulence overturning decays due to buoyancy destruction of the turbulence. A period of relatively little turbulence follows. The cycle then repeats. The onset of shear overturning is often observed to occur rather suddenly and is sometimes visualized to begin at the top of the layer and quickly proceed downward to near the surface. This phenomena is sometimes referred to as turbulent bursts. If the flow speed is very weak and the stable stratification is significant, then any significant turbulence may be inhibited entirely.

These three cases of turbulent structure are less relevant to drainage flows compared to nocturnal boundary layer flow over flat terrain. This is because the shear is not entirely surface based but may be partly concentrated

near the top of the drainage flow. Shear at the top of the drainage flow results from the fact that the ambient flow is either very weak or from a different direction; the ambient flow direction will coincide with the drainage flow direction only a small fraction of the time. Various mechanisms affecting the shear in the interfacial zone between the drainage flow and overlying ambient flow are noted below. In the case of drainage flow overriding a cold air lake or one drainage flow overriding a colder drainage flow, two or more shear zones may occur separating the various flow layers.

If the interfacial shear is weak then turbulence in this zone will not develop. With modest shear, the turbulence develops intermittently (Fig. 3c) as in Mahrt (1985). Somewhat stronger shear leads to more or less continuous turbulence in the interfacial zone as depicted in Fig. 3d. With even stronger shear (relative to the strength of the stratification) the turbulence generated by interfacial shear may extend to the surface (Fig. 3e). Of course, interfacial shear generation of turbulence may occur in concert with turbulence generated by surface based shear.

The vertical extent of the shear generated turbulence is a critical issue. For example, if the shear is confined primarily to the interfacial zone, then any suspended material diffused across the zone will not be efficiently mixed through adjacent layers. For example, consider the case of drainage flow over a cold air lake. Some suspended material in the drainage flow may be mixed across the interfacial zone into the upper part of the cold air lake. However, if the shear-generated turbulence is limited to the overriding drainage flow and the interfacial region, then little material will be mixed downward to the ground surface at the bottom of the cold air lake.

The shear in the interfacial zone and subsequent shear production of turbulence is not easy to predict or monitor. For one reason the shear is constantly changing due to the following transient effects:

1) return modification of the shear and stratification by any turbulent mixing;
2) modulation by inertial gravity waves;
3) modulation by meandering or "two-dimensional" turbulence (Lilly, 1983; Kristinsen et al., 1982; Hanna, 1983); and
4) the pulsating nature of the drainage flow (Nitsche, 1936; Aichele, 1953; Tyson, 1968a,b; Doran and Horst, 1981; Mahrt and Larsen, 1982; and Mahrt, 1985). The periodic interruptions of drainage flow can be characterized by crossflow (Schmel, 1981).

As a result of the constantly changing shear and the approximate quadratic dependence of turbulence generation on the shear, instantaneous measurements of the shear are only of limited use. A long term mean and some information of the variability of the shear is needed although such measurements are not practical in operational situations.

Even with such information, interpretation of the shear and subsequent calculations, such as determination of the Richardson number, are complicated by several additional factors:

1) The calculation of shear is sensitive to the depth scale use to determine the shear. A large value of the Richardson number corresponding to weak shear does not preclude the existence of turbulence on smaller scales. For example, thin layers of shear and turbulence may occur on scales smaller than the vertical resolution of the observations.

2) Since the shear is always changing, it's estimated value often depends crucially on the averaging time.

3) The shear and turbulence are out of phase so that small shear may partly reflect the presence of existing turbulence. After the turbulence collapses, the shear generally builds until the Richardson number falls below some critical value.

In spite of these complications and uncertainties, the user is afforded little alternative for estimating the probability of turbulence in the drainage flow or at the interface between a colder current and overlying fluid. Such a calculation seems almost necessary for comparison with other field programs. However, I consider such a calculation to be appropriate for research quality observational systems and of questionable use for observations suitable for operational use.

6. Upslope flows

After sunrise, upslope flow develops in response to heating on east-facing slopes, provided that the ambient flow is weak. The time of this development is critical to the prediction of spray transport. On east-facing slopes, upslope motion may develop within the first hour after sunrise long before the surface inversion dissipates (e.g., Banta, 1984). Orgill _et_ _al_. (1984) have observed rapid and efficient transport of contaminants up heated slopes beginning shortly after sunrise. Later, upvalley flow began to influence transport patterns.

Much less is known about upslope flows compared to cold air drainage although upslope flows have been observed as a regular climatic feature of the morning hours in some locations. Upslope flows may coexist with downslope flows on north and west-facing slopes. In fact during winter, downslope flow

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may continue on steep northerly slopes throughout the entire day. Over heavily forested north-facing slopes where little sun reaches the surface, downslope subcanopy flow may continue the entire day even though upslope flow develops just above the canopy top. Downvalley flow may also continue for several hours after sunrise before yielding to upslope flow as noted by Whiteman and Alwine (1983) and others.

The downslope and upslope flows may cooperate in terms of a mutual pressure field and in special conditions may form a closed circulation. However, the observational evidence seems to more support the situation where air is carried to the top of the ridge in the heated upslope flows and then mixed into the ambient flow. With significant ambient flow the convergence of the upslope flows occurs on the leeside of the mountain (Banta, 1984) so that upslope flow opposing the ambient wind does not reach the top of the slope. With stronger ambient flow, upslope circulations are eliminated.

Spray materials suspended in the upslope flows are not expected to reach surfaces at lower elevations at least not in large concentrations. Several factors are operating to prevent high concentrations from reaching the surface of the valley.

1) Materials mixed into the ambient flow will be mixed back downward only by means of ambient "free air" turbulence and mean subsidence both of which are weak when the ambient flow is modest enough to allow upslope motion.
2) The cold air lake at the valley floor generally survives at least two or three hours after sunrise and sometimes for five hours or more. Since the air in the cold air lake is much colder than the air near the termination of the upslope flow, mixing downward to the valley floor is opposed by buoyancy effects. In fact, the two systems are sufficiently decoupled that the upslope flow may draw air from above the cold air

lake. Upslope flow at the sides of the cold air lake may recirculate toward the center of the valley instead of continuing up the slope.

3) Turbulence in the upslope flow is not normally as weak as in downslope gravity flows. As a result, upslope flows appear to be generally thicker than downslope gravity flows. Convectively driven turbulence is expected to mix suspended spray materials within the thicker upslope flow and prevent maintenance of high concentrations.

Detailed measurements of turbulence in upslope flows are nearly nonexistent. The current laboratory studies of upslope flows conducted by James Deardorff indicate convective cellular patterns within the upslope flow. Under certain conditions, the cellular patterns dominate the motion to the extent that the upslope flow at the surface occurs intermittently.

Upslope flows may also develop at mid-day on south-facing slopes and on west-facing slopes during the afternoon. However, such development is generally less frequent compared to the cases of morning upslope flows on east-facing slopes. As the day proceeds and turbulence becomes more intense in response to surface heating; higher momentum air from aloft is mixed downward as observed by MacHattie (1968) and others. This strengthens the wind speed at lower levels which often leads to the demise of the upslope flow. This process is one reason why helicopter spray applications are usually completed in the early morning.

7. Predictability of transport

Even though drainage circulations are often quite regular, the general problem of drainage flows in complex terrain and the transport of spray materials by such transport is not a deterministic problem. That is, the transport from one point to another is generally not predictable in a practi-

cal sense. For example, the transport of a reference element is characterized by a multiplicity of "close decisions" qualitatively analogous to bifurcations in analytical treatments. Consider a reference parcel containing suspended spray material which descends the side slope of a network of many side valleys or gulleys. At the confluence of two drainage flows, the one with the reference parcel may merge, undermine or override the other drainage flow, or a combination of these possibilities. In some circumstances, the development of one of these possibilities by the flow may be altered by very small changes in the speed, depth and temperature of the incoming flows or altered by small changes in the ambient flow or generation of turbulent mixing. Changes too small to measure or model may totally alter the transport pattern with respect to a given parcel. Even if this sensitivity is not present at most of the flow confluence, a given parcel may encounter a number of such confluences as it descends and joins flows from larger slopes and valleys.

The pulsating nature of many drainage flows has been observed to strongly influence the nature of the confluence of such flows. One flow regime realized at a given confluence may yield to another regime a few minutes later. Many spray situations will be further complicated by the coexistence of drainage and upslope currents.

Consequently, the degree of predictability of transport over a complex system of slopes, valleys and subvalleys, typical of western forests is somewhat limited. Of course empirical dispersion models can be borrowed from knowledge of diffusion over flat homogeneous surfaces. The recent studies of dispersion in drainage flows over complex terrain (e.g., Reible and Shair, 1981; Barr _et al_., 1983; Gudiksen _et al_., 1984) indicate that appropriate coefficients of such relationships vary substantially and that the format of

the dispersion relationships is in some cases not appropriate. Part of the difficulty is that in the early morning over complex terrain, the spray materials will be transported and dispersed by several different types of motions, including

1) turbulence often in a nonequilibrium state;
2) drainage and upslope currents;
3) nonlinear gravity waves and transient "free" motions forced by flow over the topography; and
4) two-dimensional turbulence (meandering).

The drainage currents themselves are indeed a form of quasi-two-dimensional turbulence in that the flow component perpendicular to the terrain is suppressed by thermodynamic stability. Of course, three-dimensional aspects of drainage flows including terrain sheltering, channelling and other contributions to the convergence can be important (e.g., Gudiksen et al., 1984) even if numerically small. Even though drainage currents are quasi two-dimensional, transport by drainage currents over complex terrain is not generally deterministic. At the same time such motions are not sufficiently random to describe in terms of simplified frequency distributions or gaussian dispersion.

Although the complete spatial pattern of the drainage flow is beyond prediction the drainage flow and upslope flows at some locations may be sufficiently persistent during a given night and between nights to afford some predictability as noted in many previous studies and as recently suggested by the study of Gudiksen et al. (1984). Their study and others indicate that such persistence is significant at the surface but decreases with height and essentially vanishes in transition flow at the top of the drainage flow. In the transition region, the vertical wind shear is generally quite variable in

time due to gravity waves, meandering and local circulations on scales larger than drainage currents. These motions limit the flow persistence in the transition region.

Spray materials may become suspended in the drainage flow as in flows immediately above the drainage flow and the two-way exchange of material between the drainage flow and overlying flow is more frequent and extensive than earlier expected. The exchange between drainage and overlying flow is particularly effective at higher elevations on the slope. In any event, many transport combinations become possible and transport is not completely controlled by the more persistent drainage flow at the surface. For example, material mixed into the overlying flow may be advected downvalley at substantial speeds or transported to adjacent valleys and then mixed back downward into the drainage flow (e.g., Barr _et al_., 1983; Gudiksen _et al_., 1984). The result is that some material is sampled at the surface quicker than expected from the speed of the drainage circulation, or, is sampled at unexpected locations. In fact, material from a given release may be sampled at several different locations of considerable separation distance (Reible and Shair, 1981).

The above considerations suggest that future work would be most appropriately dedicated to rough estimates of the probability of transport between two points. To summarize the predictability problem, we mathematically formulate the flow problem by expressing the probability of a given drainage current

$$P[\vec{u}(x_0, y_0, z)]$$

where $\vec{u}$ is the velocity vector whose precise definition is not important here, z is the vertical distance perpendicular to the local surface and (x_0, y_0)

indicates the location of observations from which the probability function can be determined for favorable synoptic conditions.

As the point of interest (x,y) becomes separated from the location of observations by one or more confluences between drainage flows, the ability to estimate $P[\vec{u}(x,y,z)]$ decreases. Furthermore, as the distance $(x-x_0, y-y_0)$ increases, the considerable exchange between the drainage and overlying flow may influence the intervening transport. With increased z, the ability to estimate $P[\vec{u}]$ decreases rapidly.

To estimate the probability of transport between two points, the above probability function for velocity must be partially integrated. It may never be possible to perform such an integration, but the mathematical formulation organize the nature of the problem. In the next section we will consider estimating the probability of transport between an application site on the slope and a reference sample location such as the floor of an inhabited valley. The intention is to roughly estimate the probability of transport between two locations using observations at the two locations without consideration of the intervening motions.

8. Possible operational techniques

Four possible avenues for development of operational procedures are now outlined. These approaches are suggested for use with clear skies. The first two approaches require only relatively simple surface measurements. All four approaches ignore details of flows between the points of interest and would be subject to error. Nonetheless, their application to operational spray decisions should decrease the probability of inadvertent spray drift into critical areas.

1) For the first approach, surface temperature measurements are required at the spray site and at the valley floor or other location of concern which we call the reference site. Requirements for measurement quality are noted at the end of this section. With the first approach, the potential temperature of the spray site must exceed that of the reference site by a critical value so that spraying would proceed if

$$T_{sp} + (1\ C/100\ m) * d_z - T_r > dT_{crit} \tag{4}$$

where T_{sp} is the temperature of the spray site, the second term corrects for adiabatic warming during the potential descent, d_z is the elevation difference between the spray site and reference site, T_r is the temperature of the reference site and dT_{crit} is the required "critical" temperature difference. The physical interpretation is as follows. If the potential temperature of the spray site exceeds that of the reference site by more than dT_{crit}, then the buoyancy of the surface air at the spray site is large enough that such air will not likely penetrate downward to the reference location in significant amounts. The required temperature difference is a safety net which would reduce the probability of significant amounts of spray materials from reaching the reference location through undetermined processes such as diffusion. Spray materials suspended into air above the drainage flow would more easily satisfy (4) since potential temperature increases with height above ground on clear nights.

For lack of a better estimate, the following working value is suggested

$$dT_{crit} = 3\ C \tag{5}$$

This value is suggested for temperatures measured at 2 m. If temperatures are measured at a lower height above ground, a larger critical value would be required and so forth. Obviously, this critical value needs to be reevaluated from existing field data (if appropriate data can be found), or, from future field programs.

2) If the airflow in the spray region is thought to be significant, say greater than 2 ms^{-1} at 2 m above ground, approach 1 must be modified.

The airflow at 2 m in the spray application region may be due to a combination of local drainage flow and the influence of the ambient flow. With approach 2, the critical difference of potential temperature is first evaluated in terms of the spray site flow speed using the concept of a bulk Richardson number. In particular

$$dT_{crit} = \left(Ri_{crit}\, U^2\right)/(gd_z/T_o) \qquad (6)$$

where Ri_{crit} is the specified critical bulk Richardson number, U is the measured wind speed, g is again the acceleration of gravity, d_z is the elevation difference and T_o is a basic state temperature. $Ri_{crit} = 2$ is a suitable first guess, however as with approach 1, reevaluation is necessary. Application of this relationship proceeds as follows. If the temperature difference on the left hand side of (4) exceeds the critical value estimated from (6), then the strength of the stratification is judged to be strong enough to limit the probability of significant concentration from reaching lower elevations. Otherwise the turbulence is predicted to be strong enough to cause significant vertical mixing and perhaps even elimination of the drainage flow system. If relationship (6) predicts a smaller value than (5), then the value of dT_{crit} from (5) is applied.

Since spray material is transported by the ambient flow as any drainage transport, one must consider the influence of ambient wind direction with respect to the direction of the sample location from the release point.

Although the ambient direction is usually quite variable, this variability often decreases with increasing ambient flow speed.

3) If economically justified, passive tracers could be released about two hours prior to the scheduled spray application and sampled at the reference site. This approach is much more direct than the previous two but is still vulnerable to nonstationarity of the airflow where conditions change significantly between the passive scaler release and the spray application. If the passive tracer first arrives at the sampling unit more than two hours after release, the transport rate is probably sufficiently slow that substantial dilution would result.

   Previous research field programs have used primarily sulpherhexaflouride tracer (Gryning and Lyck, 1983; Orgill and Shreck, 1984; Schmel, 1981, and Dickerson, 1981) although smoke, oil fogs and perfluorocarbon tracers have also been used. Additional tracer techniques are noted in Barr (1983).

4) Use of numerical models to predict material transport by cold air drainage is not recommended for operational use for three main reasons:

   a) such models require real time initialization since short term numerical integrations are generally sensitive to such initialization. Such initialization is expensive and tentative and probably too time demanding to use on a real time basis;

b) such models require gridding of the terrain which is too expensive for operational use where the site location often changes between applications; and

c) such models have not been evaluated for a variety of terrain types and flow situations.

For research purposes, the reader is referred to the numerical model of Yamada (1983). The terrain will normally be far too complex for application of analytical models as discussed in the Introduction. For a recent survey of such models, the reader is referred to Mahrt (1982).

Although approaches 1 and 2 do not explicitly include a number of influences on the transport, they are thought to be the most plausible possibilities for practical operational use. However, such approaches require certain quality control requirements for the temperature observations. In particular:

1) The thermistor should be calibrated over the expected temperature ranges and should have an accuracy of better than 0.3 C. The latter is not normally a stringent condition.
2) Temperature measurements need to be made at the same height above the ground at both locations.
3) The preferred height above the ground is 2 m. Measurements below 1 m are strongly influenced by micro features such as the presence of rocks, bushes, etc.
4) The thermistor should be properly ventilated in order to be in contact with "outside" air.
5) The thermistor should be shielded from overhead radiative heat loss. Otherwise the thermistor could read more than 5 C too cold.
6) Near-surface temperatures under stable conditions or conditions of radiative cooling are spatially noisy and vulnerable to microscale varia-

tions. Temperature measurements should be made at more than one place within the potential spray region and within the reference region where protection is desired.

7) Temperature measurements should be made for at least a one-hour period since drainage flows often oscillate or occur as pulses, generally with a period of ten to thirty minutes. Any significant trends due to changes of external conditions also need to be assessed.

Just before and around sunrise, the diurnal trend of temperature is normally quite weak. One solution is to use temperature sensors which are mounted on a cable to a lightweight instrument box and twirled by the observer. The twirling motion augments contact with the air to the extent that the radiation problem is unimportant. Such instruments can be hand carried allowing a quick survey of the region. The observer should choose a route so that the same micro-location is sampled roughly every 15 minutes for a total of at least 4 samples. The observer must evaluate any idiosynchrosies of the particular instrument. For example, some instruments may give errors if the unit is not held approximately level and may produce a certain unrealistic response when batteries are low. For most observers, twirling the sensor just above head level will provide an adequate 2 m measurement.

Wind measurements can be implemented with hand held anemometers. Sampling problems analogous to 6) and 7) must be recognized. In addition, the observer should include the most exposed parts of the application region.

9. Recommended field work

This report recommends field work which would evaluate the potential use of approaches 1 and 2 in the preceding section. Such field work would consist

of the simple temperature and wind instrumentation mentioned in the preceding section and the release of tracers with sampling units to calibrate and evaluate approaches 1 and 2. A more general goal would be to establish the nature and degree of the relationship between spray transport and the potential temperature difference between the release and reference site.

Such field work would best begin with relatively simple terrain situations and would require a significant number of cases, at lease twenty to thirty. Regions with chronic mesoscale systems should be avoided for initial work. Such mesoscale systems include circulations related to marine air invasion and mountain valley winds on the scale of major mountain ranges. Such circulations cannot be entirely avoided; fortunately, they often exert little influence in the morning hours at most locations in the Western United States.

The choice of a seasonal period between 1 July and 15 September should minimize complications due to synoptic disturbances. Still, many days would be eliminated due to significant ambient flow associated with meso or synoptic scale pressure and gradients. Circulations associated with thermal lows and the subtropical high pressure system off the Pacific coast is one example where substantial ambient flow is maintained without a so-called weather disturbance.

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Glossary

adiabatic warming or cooling: descending air warms due to compression as it encounters higher pressure. Ascending air cools due to expansion as it encounters lower pressure.

ambient flow: here defined as the flow above the cold air drainage. This flow may be quite complex and height-dependent although for purposes of discussion it is implicitly assumed to be constant.

cold air drainage: movement of cold surface air downslope due to the action of buoyancy.

cold air lake: a pool of cold air which settles in a low-lying area.

drag coefficient: relates the surface air drag (rate of momentum loss to the surface) to the square of the surface wind speed. The value of this coefficient decreases rapidly with increasing stability of the air.

entrainment: a turbulent fluid engulfs or pulls in blobs of external fluid thereby increasing the total mass of the turbulent fluid. With detrainment, blobs of turbulent fluid "escape" or are detached from the turbulent fluid.

episodic mixing: turbulent mixing which occurs as well-defined events separated by periods of little turbulent mixing.

frost pocket: location of persistent coldest nocturnal temperatures often but not always occurring with concave terrain curvature.

gravity flow: here used synonomously as cold air drainage.

interfacial region: fairly sharp transition region between the cold air drainage and ambient flow.

mesoscale motions: air motions on the scale of a few kilometers up to one or two hundred kilometers. Examples include marine air penetration, squall lines, and fronts.

nocturnal inertial oscillation: systematic rotation of the ambient wind direction frequently observed shortly after sunrise and continuing throughout the night.

Richardson number: generally the ratio of the influence of buoyancy to the influence of shear. The Richardson number occurs in many different forms.

slope Richardson number: the product of the Richardson number and the terrain slope.

slope-valley winds: airflow up and down the valley side slopes join with circulations up and down the valley floor to form one flow system.

synoptic scale: air motions on the scales of a few hundred kilometers to a thousand kilometers. Examples include low pressure storm systems and high pressure systems.

transition region: a layer of air, possibly quite thick, above the cold air drainage where the wind changes with height between the drainage wind at the bottom of the transition region to the ambient flow at the top.

List of Symbols

C_D	drag coefficient
dT_{crit}	required temperature excess of T_R over T_{SP} after adiabatic correction
d_z	elevation distance between spray site and reference or sampling location
g	acceleration of gravity
P	probability
Ri_{crit}	critical bulk Richardson number
S	slope magnitude
T_0	average surface temperature
T_R	surface air temperature at the reference or sampling site
T_{SP}	surface air temperature at the spray site
u	downslope flow component
U	surface wind speed
x	downslope distance
y	cross-slope distance
z	upwind distance perpendicular to the slope
θ	deviation of potential temperature from average value
θ_0	average potential temperature

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